SUBSIDENCE MANAGEMENT AT NEW MINERAL CITY MINE, FORT DODGE, IOWA

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INTRODUCTION

U.S. Gypsum's New Mineral City Mine is located on the outskirts of the City of Fort Dodge, Webster County, Iowa (Figure 1). The underground mine workings have been inactive since 1927, and operated for about 30 years concurrent with several other competitive underground mining operations in the Fort Dodge vicinity. Historical mine development consisted of drilling and blasting methods in a room-and-pillar configuration. The mining seam is situated 60-70 ft below the regional ground surface. The mined voids are partially flooded.

Figure 1. *Present-day USG Fort Dodge, IA manufacturing facility and transportation infrastructure. New Mineral City Mine underlies much of photo area.*

U.S. Gypsum (USG) continues to operate surface quarries and gypsum processing facilities in the Fort Dodge area, and large areas of the plant facility are situated over the inactive New Mineral City Mine. Public roads, rail lines and other utilities are also situated above mined voids. This paper describes how USG is managing mine-related subsidence issues in connection with the undermined roads, rail lines, and active mill facilities.

Although mine-related ground subsidence events had occurred sporadically over many years around the plant site, it was not until 1989 that USG accepted a preventive philosophy to mitigate higher-risk areas by implementing a phased project. Prior to 1986, subsidence features had been reported, but had not happened frequently enough or had enough of an impact to require a large remediation program. Site specific programs for underground inspection and pillar stress analysis were conducted in 1985 for new building construction. Remediation efforts from 1989 to 1999 involved mostly pneumatic backfilling methods that required personnel to work underground to accomplish the task. Because MSHA rules prohibit USG personnel from entering the mine without renewing an operating permit, specialty contractors have been used in the program whenever possible.

The phased program was accelerated to include TDR monitoring, hydraulic backfilling, gravity backfilling and borehole camera inspections after a significant subsidence event on January 12, 2002 damaged a business building near USG plant facilities. The event occurred during non-working hours. Because of the location of the building over mined workings and the severity of the damage, USG senior management decided that a full re-evaluation of the subsidence potential be conducted and that a modified remediation program be implemented.

Prioritizing sites for remediation/monitoring was done through detailed mine inspections, geological characterization, subsidence history reviews, and subsequent demarcation of risk areas. The risk areas were classified based on 1) general subsidence/caving potential and 2) potential impact to both public and USG assets. Safety of employees and the traveling public was a priority in consideration of risk. Intensive field monitoring and remediation, as described herein, began during July 2002.

GEOLOGICAL CHARACTERIZATION

The New Mineral City Mine was developed in beds of the Upper Jurassic Fort Dodge Formation (Cody et al., 1996). The gypsum seam is up to 25-ft thick and subcrops beneath about 50-ft of unconsolidated Pleistocene glacial till (Figure 2). The economic gypsum deposits of Webster County are disconnected evaporite bodies that are erosional remnants of a once extensive evaporite system. The gypsum bodies are generally flat-lying to mildly folded, and are preserved within down-dropped fault blocks along an eas-west trending basement fault complex. The till is generally composed of clay-rich beds with interbedded, sand filled paleo-stream channels. The geomorphology of the site is generally a flat, featureless glacial outwash plain dissected by small tributary streams of the Des Moines River valley.

The Fort Dodge gypsum deposits have been affected by natural karst processes to the degree that dissolution enlarged joints impact current quarrying practices (Figure 3). It was through studying these types of features that USG personnel gained insight toward an effective approach for selective remediation in evaporite systems.

Figure 4 shows a field example of a sinkhole that has progressively developed along a pit wall during the course of quarry development in a previously underground mined area. Dissolution joints in the gypsum that have been intercepted by underground mining allow water-saturated sediments to flow downward into the mined void, and the cavity left by the displaced sediments propagates upward as sediments continue to slough and fill the void. This process will continue until the void breaches the surface as a sinkhole, or sediment has choked-off the local mined void and joint conduit.

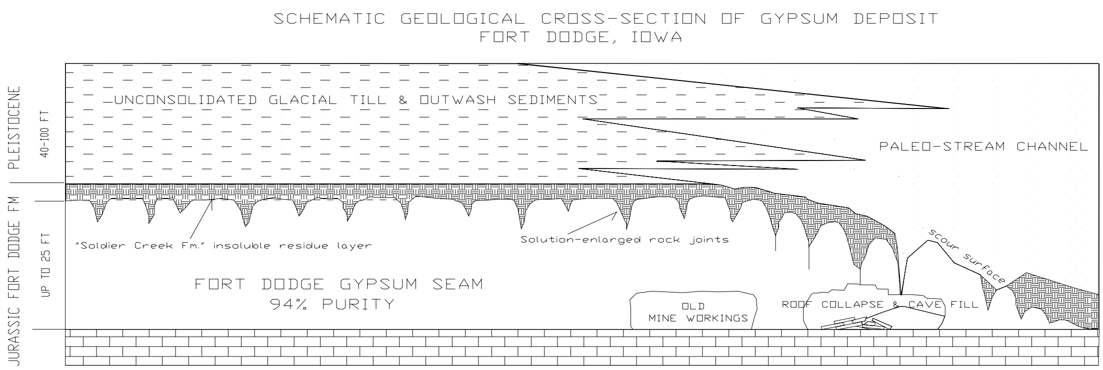

Figure 2. *Schematic section of the USG gypsum deposit, overburden materials and mine workings.*

Figure 3. *Linear dissolution features at top gypsum, USG Flintkote quarry*.

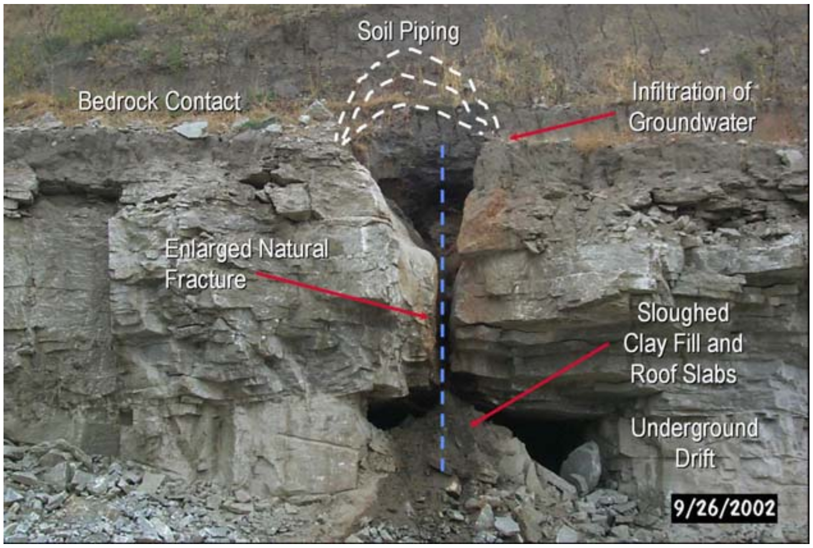

Figure 4. *Sinkhole developed in quarry wall showing how dissolution joint/fracture intercepted by old underground mine workings accelerates sinkhole formation. Gypsum seam is about 25 feet thick.*

With an understanding of the dynamics of sinkhole formation at Fort Dodge, underground mapping was done of the dry, accessible parts of the New Mineral City Mine. This was undertaken to identify and accurately locate geological features such as major joints or holes in the mine roof. It was especially important to note those features containing soil materials and evidence of water seepage. Some parts of the mine were found to be clogged with mud flows; a direct indication of connection with overburden materials that had piped through joints in the gypsum.

The roof beam rock of the mine consists of flaggy- to massive-bedded gypsum, and is generally 10-15 ft thick except where thinned by dissolution in localized areas. Mine room heights are about 15-ft, but pinch down to 8-ft in the main haulage entries. Mining was generally restricted to the lower half of the total seam thickness for stability reasons.

RISK ASSESSMENT

The process of determining at-risk areas involved several steps geared toward identifying and prioritizing specific areas for remediation or monitoring. First, the mine and its geological features that were mapped as part of the characterization process were correlated with surface facilities. This was done through surveying spot checks conducted during characterization mapping followed by creating digital maps. Digital aerial planimetric maps were then constructed and migrated over the digital mine maps for correlation with surface facilities. Significant geological details, such as mine roof joints, were plotted on the composite maps along with known locations of historical sinkholes and trough collapse areas.

Next, prioritizing of sub-sites hinged on developing a philosophy of approach to the problem. USG's philosophy is to monitor an area before remediating, with the intent of eventual remediation. Also, sites would be monitored or remediated that posed potential for injury to the public as well as employees, or posed potential for damage to USG's manufacturing assets. Viewed in this way, USG adopted the practice of assigning composite site risk values based on 1) the likelihood, or event potential, of subsidence happening at a point, and 2) the impact of that event on people and infrastructure (Ruegsegger, 1998).

For determining composite risk values a set of criteria were developed to be applied as risk factors as follows:

- Mine areas with high extraction ratios or splintered pillars
- Ground surface areas with history or direct evidence of sinkhole formation (mine inaccessible)
- Mine areas with cribbed roof fissures, water seepage, or large fissures/joints
- Mine areas near mine-level mud flows
- Ground surface areas with poor surface drainage

Determining the potential impact of a risk factor is a straightforward process of noting the coincidence of a number of criteria with the following impact categories:

- Plant Assets (buildings, walkways, utilities, structures necessary for manufacturing and storage of raw materials, open fields within property boundary)
- Public Assets (utilities, roads, communications assets)
- Plant Traffic (truck marshalling yards, average daily traffic volume)
- Public Traffic (average daily traffic volume of cars, trucks and trains)

Sub-sites were delineated on the composite map based on the locations of physical features on the impact categories list. The composite risk for a sub-site was determined by assigning subjective weight factors to each impact category and comparing them to sub-sites having risk factors. Once identified, the at-risk sub-sites were ranked as to priority for remediation or monitoring.

REMEDIATION AND MONITORING SUB-SITES

Four remediation sub-sites are presented in this paper: 1) the USG employee parking lot, 2) the USG paper warehouse facility, 3) the Canadian National-Illinois Central railroad, and 4) Mill Road (public). These areas comprise Phase I and part of Phase II of a multiphase, multiple-year remediation program, and are representative of the scale and scope of the overall project. The employee parking lot was designated for monitoring only until cost effective remediation or relocation could take place at some future time. The general configurations of these undermined areas are shown in Figures 5-8.

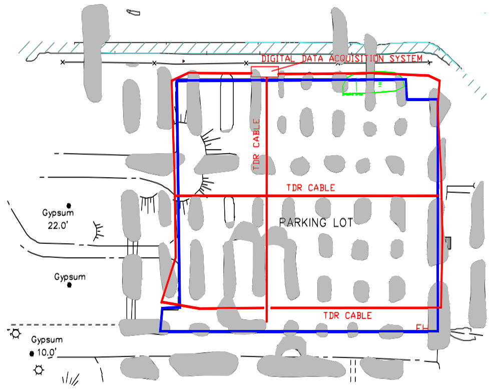

Figure 5. *Employee parking lot sub-site.*

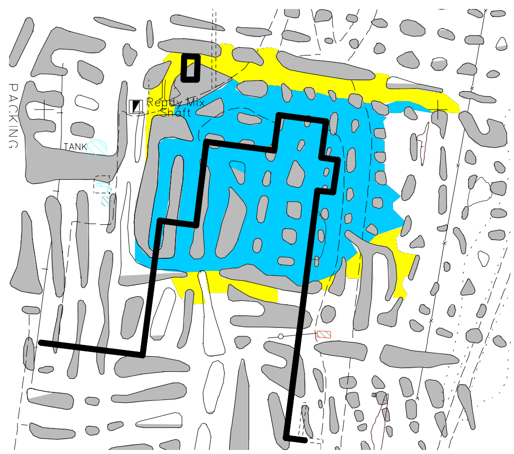

Figure 6. *Paper Warehouse sub-site. Outline of building in heavy black line.*

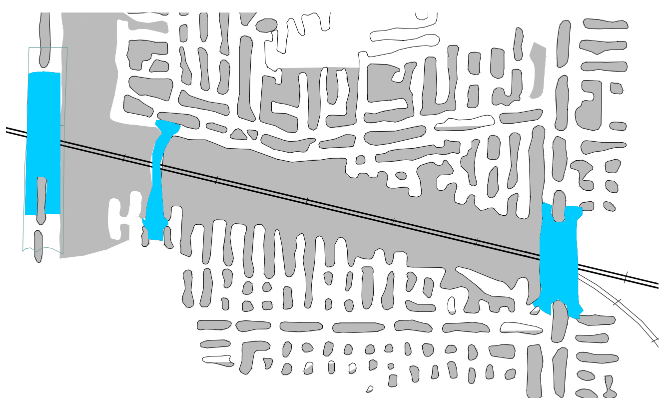

Figure 7. *Canadian National-Illinois Central Railroad sub-site.*

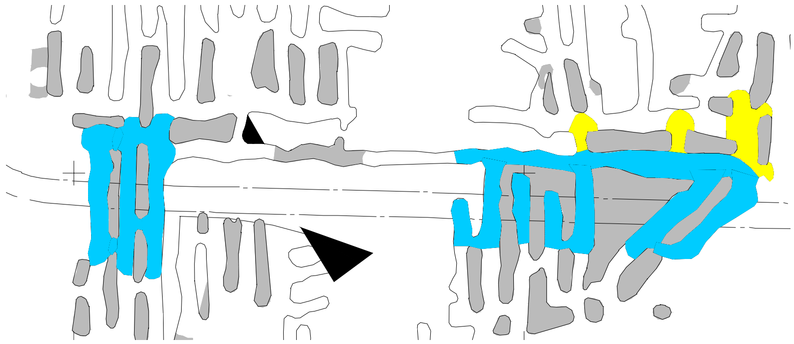

Figure 8. *Mill Road sub-site.*

SUB-SITE REMEDIATION AND MONITORING TECHNOLOGY

Backfilling

In consideration of the mine room-and-pillar geometry and observed geological conditions, USG chose hydraulic backfilling as the primary remediation method. Backfilling through boreholes for remediation can be done in a relatively short period of time and minimizes the risk exposure of employees to underground working conditions.

The required volumes and dry tons of backfill materials were calculated for each undermined risk area where backfilling was to be applied in Phase I. This was done for budgeting, logistical and planning purposes. All boreholes planned for inspection and backfilling were then sited using GPS and conventional surveying methods.

The strategy guiding the backfilling operations was, for each sub-site, to drill a series of 8” diameter vertical holes through which 1-inch minus dry crushed limestone aggregate was introduced by gravity into mined voids. These holes were drilled into the mine in a pattern around the perimeter of the identified risk area and completely filled using a front-loader. These aggregate piles were to form conical dams and sediment traps for subsequent hydraulic backfilling interior to the pile arrangement.

After placement of crushed limestone aggregate by gravity backfilling, angled, steel-cased boreholes were to be emplaced so that 3/8-inch minus crushed rock could be precisely introduced into the mine as slurry. This type of hydraulic backfilling technique would permit building up sub-horizontal sheets of rock fines (manufactured sand) that would dewater through the gravel piles and then vertically compact (Figure 9).

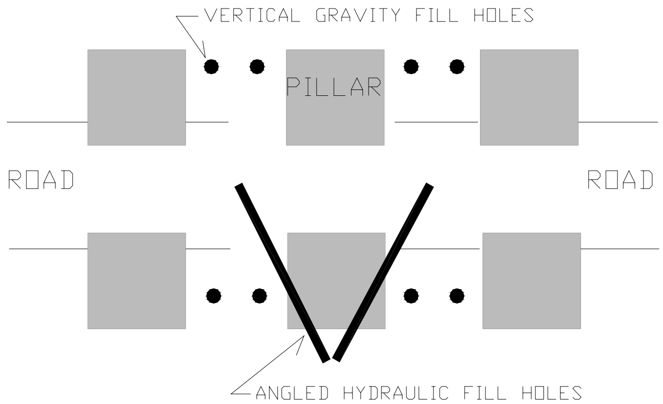

Figure 9. *Conceptual plan sketch of gravity fill hole arrangement between mine pillars. These are located on both sides of a road at the surface. Sand-size materials are then pumped into mine voids as a slurry through angled, cased holes for precise placement. Dewatered slurry compacts for firm support.*

Controlling the flow direction of the injected slurry was a major concern for backfilling effectiveness and economy. This method was only considered for areas where the mine was not flooded. A Marks Products borehole microcamera and Sony camcorder were used periodically during hydraulic slurry backfilling to monitor progress, fill pile distribution, and for aiding in precise placement of additional angled holes in response to meandering effects of the fill pile. Where appropriate, the mine floor topography was used as part of borehole placement and in sequencing of the backfilling. For a particular injection hole, slurry was to be injected until refusal.

The principle of hydraulic backfilling was to provide a substantial pad of compacted material that would mitigate the piping effect of loose, fluidized overburden materials into the mine through dissolution features in the gypsum mine roof. Although a minor volume of void space was expected at the top of the fill pile due to mine roof irregularities, it is theorized that any rock delamination into the remaining void space would be severely limited and would not telegraph to the surface. The compacted 3/8-in minus backfill material would also encapsulate the mine pillars, thus providing additional mine support.

Two USG-built stowing units were used for mixing and pumping the slurry (Figure 10). A unit consists of a hopper with vibrating discharge, a belt conveyor, a mixing tank with agitator, and a centrifugal suction pump. Front loaders fed the manufactured sand (3/8-inch minus) into the hoppers. Pipelines consisted of HDPE and steel pipe. The mixing tank volume is about 2,250 gal capacity. The daily injection rate capacities of the stowing machines were to be determined during the course of the project through experience with maintenance and logistical issues.

Figure 10. *Backfill stowing machine set-up; hopper, conveyor, mixing tank. Portable lights for round-the-clock operations.*

Monitoring

Time Domain Reflectometry (TDR) methods were employed for subsidence monitoring at select plant sites until appropriate remediation could be initiated. Automated and conventional TDR monitoring using coaxial cables has been described in detail by O'Connor and others (O'Connor et al., 1999, 2002).

Time-Domain Reflectometry (TDR) systems were installed at the paper warehouse facility and at the employee parking lot . At the paper warehouse three 7/8-in diameter coaxial cable installations were placed around the periphery of the building for monitoring before and during backfilling operations. These were placed in 3-ft deep excavated trenches and covered with 6-in of engineered grout formulation. The grouted cables were then buried and electronically tested. Encasing the cable in grout in this way would keep the cable rigid over spans, or upward propagating subsidence chimneys, up to 5 feet in diameter. The cables were then interrogated daily for movement using a conventional Tektronix 1502B cable tester. A total of 470-ft of coaxial cable were used at the paper warehouse.

The TDR system emplaced at the undermined employee parking lot consists of 1,940-ft of 7/8-in cable grouted in trenches that loop around and cross the parking lot (Figure 5). The five separate cable installations were sited based on geological considerations obtained from drilling, underground observations and historical mine maps. The parking lot system was designed to be a semi-permanent installation until USG could either move the parking lot or determine another cost effective method of remediation. The installations are monitored continuously using a centralized, automated cable-interrogation system with autodialer call-out alarm capabilities (Figure 11).

Figure 11. *Automated data acquisition system installation at employee parking lot.*

Evidence for surface subsidence activity was also monitored along Mill Road and the employee parking lot by daily visual inspections augmented by digital photo imaging.

Backfilling activity was periodically monitored using borehole microcamera inspections, fill pile elevation checks through boreholes with weighted surveying chains, and by direct underground observations using a mine engineering contractor.

RESULTS

Backfilling

Figures 6, 7, and 8 show the completed backfill piles as shaded regions. All hydraulic backfill holes were injected with slurry to pressure refusal. Microcamera monitoring in all backfilled areas showed that the hydraulically emplaced, manufactured sand was dammed effectively by the coarse aggregate gravity fill cones, and that clear water was decanting from the fill piles. Therefore, loss of fines was kept to a minimum and the solid fractions are indicated to have dropped out of the slurry quickly after injection into the mine. Contractor underground inspections of the fill piles verified the effectiveness of the coarse aggregate cones, and they found that the hydraulically emplaced sand was compacted to the point that boot prints were barely discernible on the pile surface.

The stowing systems and three-man crews were able to inject between 400-500 tons per day of “dry” manufactured sand using both units. Water availability was essentially unlimited due to sufficient pumping from the inactive mine water pool. Stowing system operations and hydraulic backfilling were curtailed from late December 2002 to late March 2003 because of logistical problems associated with winter weather.

The below table shows the detailed backfilling results by sub-site area. The employee parking lot has not been backfilled and is not shown in the below table. Six vertical holes were drilled into the parking lot area for geological characterization.

	Paper Warehouse	CN/IC Railroad	Mill Road
Days for backfilling	120	52	83
Tons gravity fill	7,034	2,860	8,140
Tons hydraulic fill	45,039	8,784	25,978
Quantity gravity fill holes	42	17	38
Quantity hydraulic fill holes	27	5	16
Actual / predicted tons ratio	1.22	0.4	0.98

The average time to fill a vertical hole with aggregate using a front-loader was 4.5 hours. Therefore, the major amount of time involved in backfilling was for hydraulic stowing operations Drilling for backfilling was often done ahead of, and concurrent with, backfilling operations. All backfilling operations including periodic maintenance were done 24 hours per day, 7 days per week.

Including all four sub-sites discussed in this paper, there were 151 boreholes drilled. Of these, 145 were used for backfill remediation. About 1.5 to 2.0 holes were drilled per day. Angled drill holes were cored through the gypsum sections to check for joint propagation and roof beam thickness. These holes were drilled at angles ranging from 27^0 to 75^0 from the horizontal.

TDR

The only limitations noted during the monitoring period were that extreme cold temperatures (<10^0F) affected the coaxial cable multiplexer and some cable connections. To resolve this, USG staff installed a small heater for the instrumentation box and added deep-cycle marine batteries for consistent power supply. The basic monitoring unit is a 12 VDC system operated by solar panels, and it was considered that the impact of long periods of overcast weather in combination with instantaneous amp drawdowns on the original battery powering the multiplexer contributed to artifact alarms. Loose cable connections causing cold-temperature artifact alarms were also tightened. After all these changes were made the artifact alarms ceased.

A single angled-hole TDR cable was installed concurrent with backfilling operations at the paper warehouse facility to monitor the effects of backfilling on sediments overlying the mine. This cable extended from the surface to a point under the center of the facility and was anchored into roof-beam gypsum above the mine. As shown in Figure 12, shear movement occurred at a linear rate at three points along the cable during backfilling. This movement continued for about 2 months beyond completion of backfilling operations at that sub-site on May 5, 2003. We believe that the backfill materials, as they piled around the mine pillars, caused a significant change in the mine envelope stress field such that the change in the stress field was translated to the soft sediments overlying the mine. After a period of about two months after completion of the backfill operations, the stress adjustments had largely ceased, as indicated by a relaxation of the TDR cable displacements.

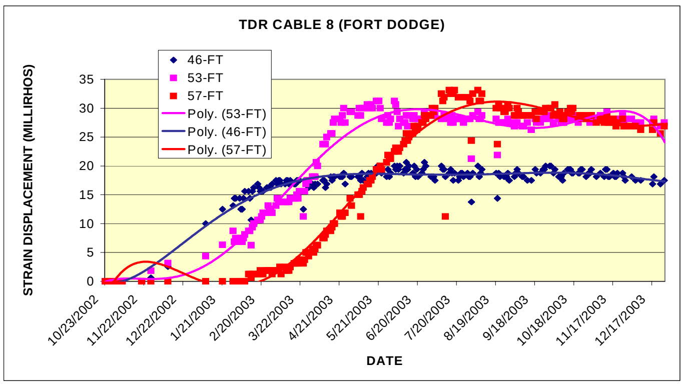

Figure 12. *Time-displacement history plot of movement along angled-hole cable under the paper warehouse.*

Costs

General operations unit costs are summarized in the following:

- Automated TDR cable system cost with one digital data acquisition unit: $30,000
- Drilling costs averaged $1,300 per hole
- Gravity coarse aggregate backfilling cost was $9.25 per ton dry materials
- Hydraulic backfill manufactured sand cost was $12.96 per ton dry materials

SUMMARY

USG's backfill remediation program to-date has cost $3.3 million. Visual underground inspections indicate that the combination of gravity fill piles and slurry infilling effectively sealed the mine workings where applied. TDR monitoring is a cost effective means of continuous monitoring over lower-risk areas compared to backfilling costs.

REFERENCES

Cody, R.D., Anderson, R.R., and R.M. McKay, 1996, Geology of the Fort Dodge Formation (Upper Jurassic), Webster County, Iowa: Iowa Department of Natural Resources Geological Survey Bureau Guidebook No. 19, 74 p.

O'Connor, K.M. and C.H. Dowding,1999, *GeoMeasurements by Pulsing TDR Cables and Probes*: CRC Press, Boca Raton.

O'Connor, K.M., Ruegsegger, R., and K. Beach, 2002, Real Time Monitoring of Subsidence along Interstate I-77, Summit County, Ohio: Fourth Biennial ITGAUM Abandoned Underground Mine Workshop, Davenport, Iowa.

Ruegsegger, R., 1998, Manual for Abandoned Underground Mine Inventory and Risk Assessment: State of Ohio Department of Transportation.